Autonomy
@ Ames
NASA Ames Research Center

Rational and Deterministic Autonomy

Rationalism and Determinism in Autonomy means having the right kind of goals and the ability to select the right goal from an existing set.

Determinism enables easier verification and validation.

The challenge is:

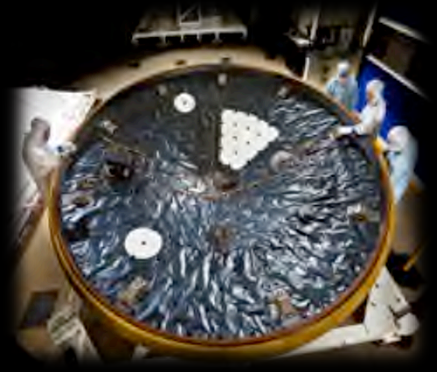
- **Definition of rational goals**
- **Engineer a deterministic autonomous system**

Valid Requirements → Rational Goals

Good Engineering → Determinism

Core Competencies @ Ames

Air Traffic Management

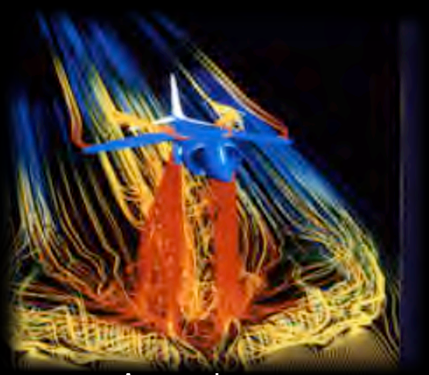


Entry Systems

Advanced Computing & IT Systems

Intelligent / Adaptive Human & Robotic Systems

Low-Cost Space Missions



Aerosciences

Astrobiology and Life Science

Space and Earth Sciences

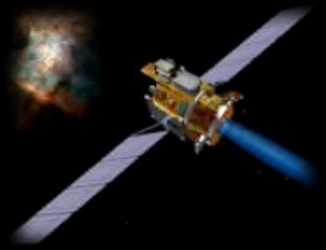
Ames Intelligent / Adaptive Human and Robotic Systems Core Competency

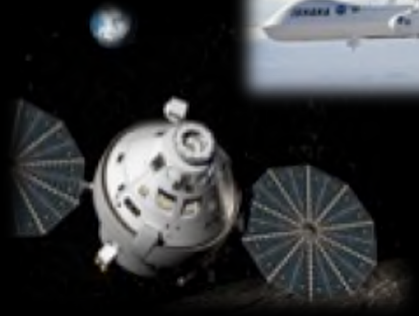
Engineering, computer science, and human factors skills and technologies.

Applied to develop and deploy intelligent systems often operating in complex and varying levels of collaboration with humans to:

- extract knowledge, including state awareness
- support decisions, and
- enable adaptive system operations

Operating in dynamic space and aeronautics mission environments.





Ames Intelligent / Adaptive Human and Robotic Systems Competency Elements

KNOWLEDGE & STATE AWARENESS

Collaborative Assistant Systems
- Enable distributed teaming & knowledge extraction

Discovery and System Health
- System diagnostics, prognostics, physics models

MACHINE SYSTEMS

Autonomous Systems and Robotics
- Planning, scheduling, machine learning, advanced controls, & intelligent robotics

HUMAN SYSTEMS

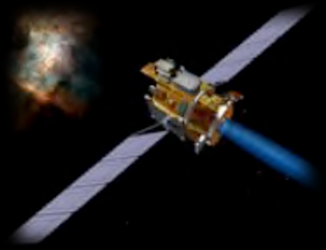
Human Performance & Psychophysiology
- Human vision, audition, attention, memory, and cognition

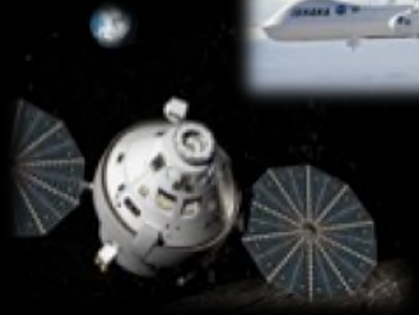
Human-Computer Interaction
- Human-centered interface design & usability

CROSS-CUTTING METHODS

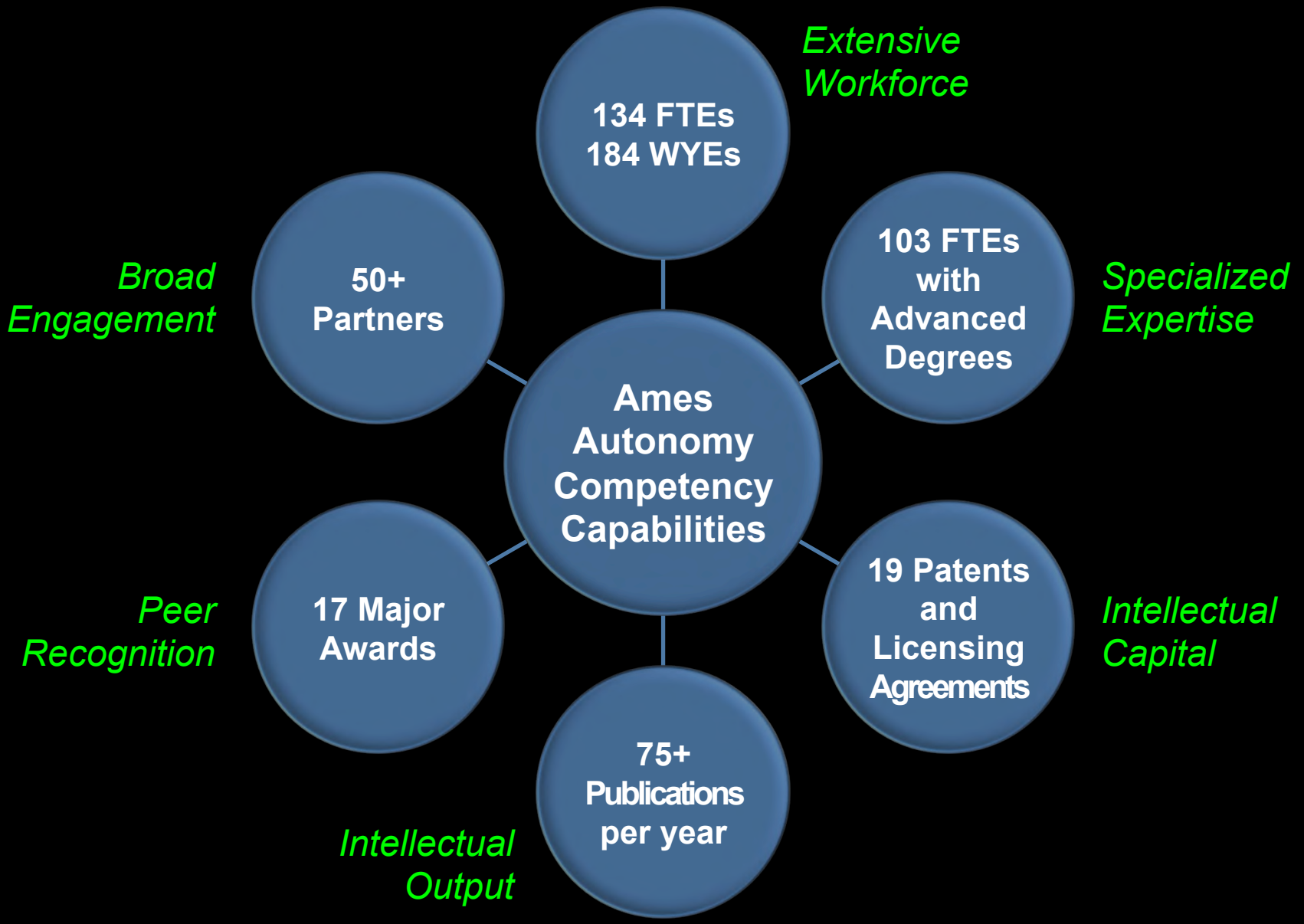
Collaborative Autonomy
- Methods to enable effective human-machine and system performance

Robust Software and System Engineering
- Verification & validation of software and system performance

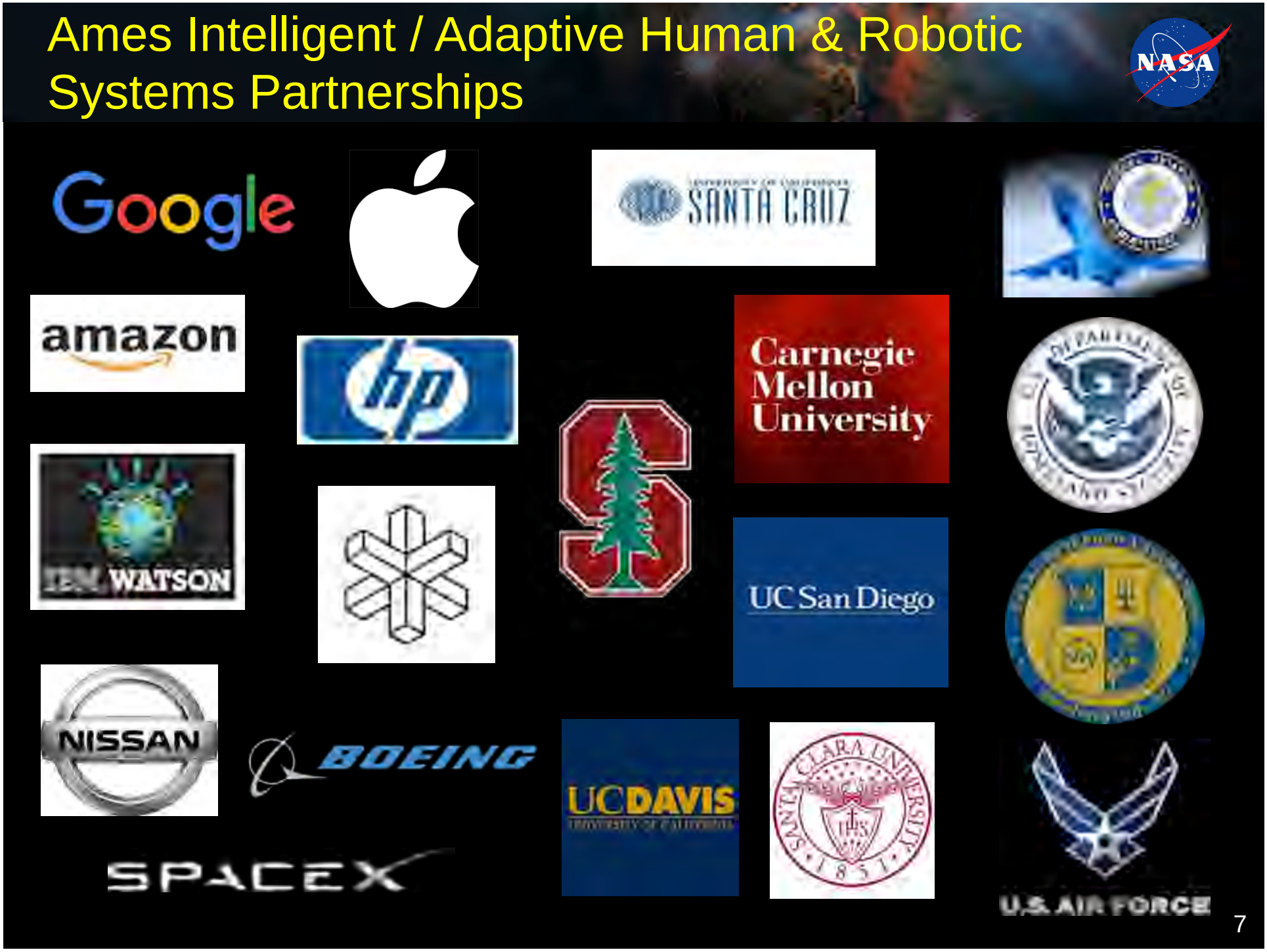




Ames Intelligent / Adaptive Human & Robotic Systems Workforce

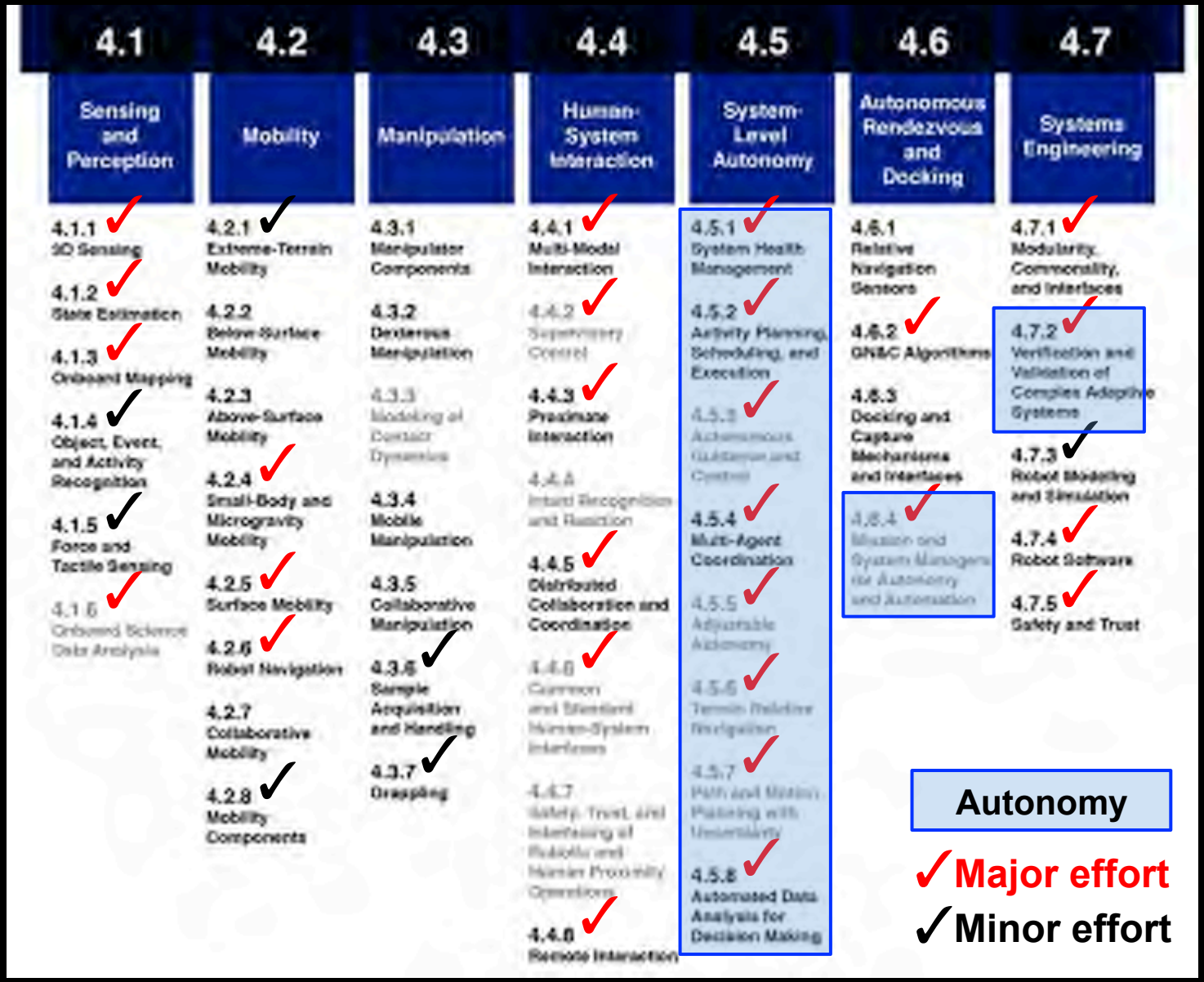


Ames Intelligent / Adaptive Human & Robotic Systems Partnerships



Autonomy Technology Development at Ames

TA4: Robotics and Autonomous Systems



Ames Autonomy for Space Exploration

2003 Mars Exploration Rovers

Mixed-Initiative Activity Planner (MAPGEN)
Collaborative Information Portal (CIP)
MERBoard Collaborative Workspace

4.5.2

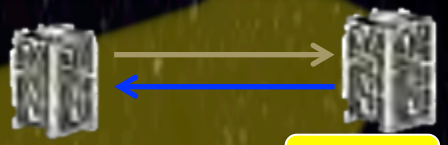
2007 Phoenix Lander

Ensemble:
Rover activity planning & scheduling

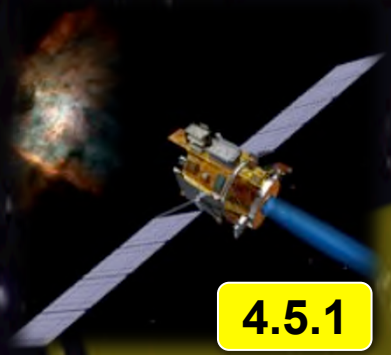
4.5.2

2016 NODES

Spacecraft swarm relaying ground commands and science data between satellites while autonomously determining order of satellite network communication



4.5.4



4.5.1

1997 Deep Space 1 Remote Agent

The first demonstration of an onboard autonomous spacecraft control system

4.5.1

2005 Earth Observing - 1

Livingston on-board model-based diagnostic

4.5.2

2012 Mars Science Lab

Ensemble:
Rover activity planning & scheduling

4.5.2

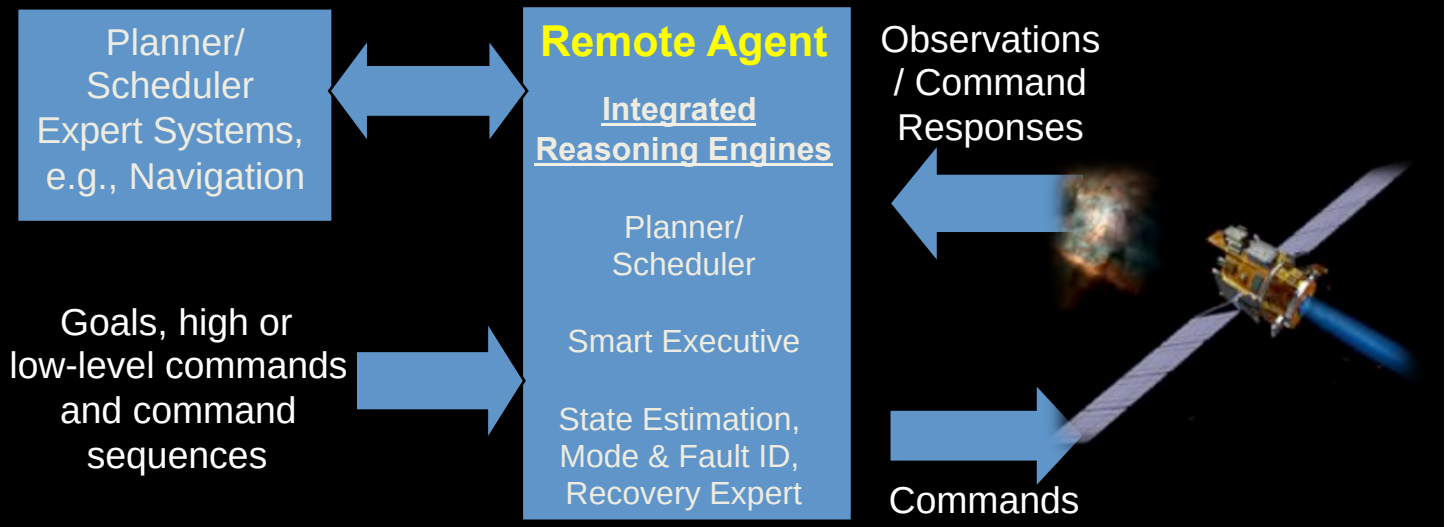
2015: AMO

Demonstrate crew autonomy protocols and technology onboard ISS

Deep Space 1 – Remote Agent (1997)

TA 4.5.1, 4.5.2

The first onboard artificially-intelligent adjustably-autonomous flight system to control a spacecraft – 1999 NASA Software of the Year winner

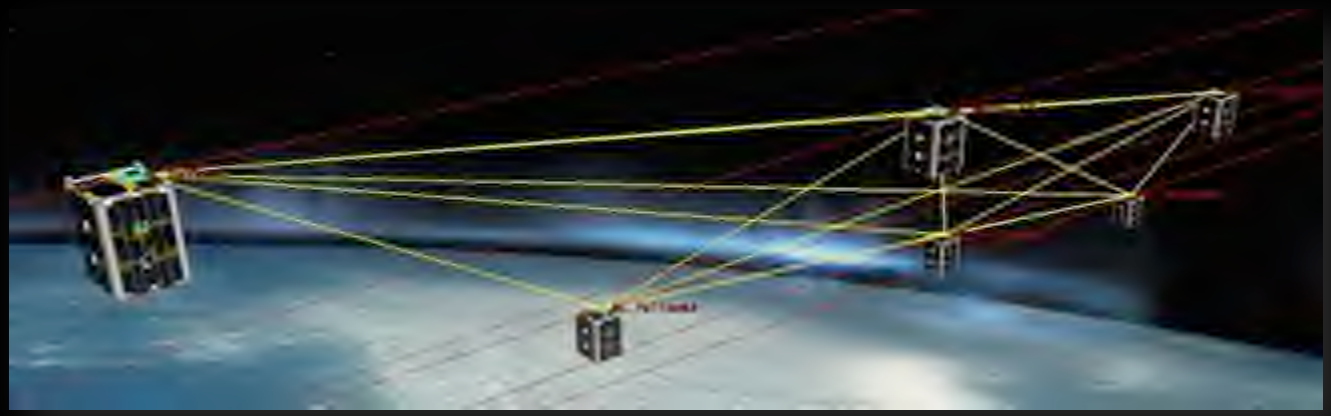


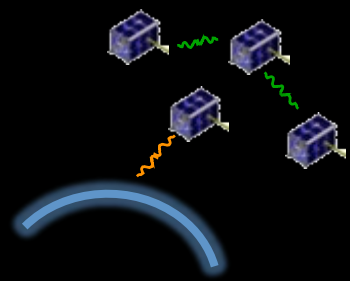
Capabilities

- Planner expands high-level goals into flexible plans
- Executive decomposes plans into low-level spacecraft commands and monitors that the states commanded to are achieved and maintained
- Logically-Consistent State Estimator and Fail-operational fault recovery
- Identifies faults and suggests recoveries that the Executive uses to continue plan execution
- If necessary, Executive requests the Planner to generate a new plan

Nodes (2016)

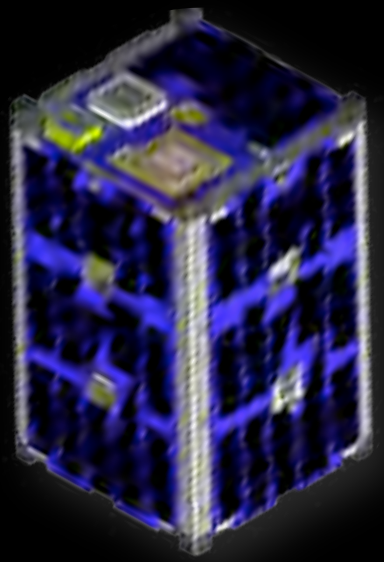
EDSN: A Nanosat Swarm





Small Spacecraft Technology Demonstration:

- **Novel intra-swarm communications**
  - The first true Swarm in space. Configured to allow spacecraft to talk to each other and share data, while taking geographically dispersed payload measurements
  - 1 spacecraft talks to Ground for the whole Swarm.
- **Multi-point space physics (radiometers)**



- NASA Ames – PM and S/C bus
- Montana State University – Instrument
- Santa Clara University – Ground Station

EDSN spacecraft is a 8x 1.5U nanosat technology mission from NASA's Space Technology org

Ames Human-Autonomy Teaming for Space Exploration

2007 Phoenix Lander

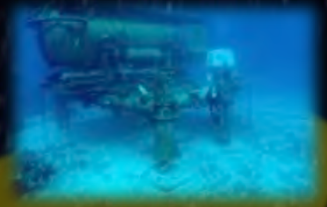
Activity planning & scheduling by science teams

2012 ISS MCC

Integrated Attitude, Power and Crew Activity Planning for Mission Operations at JSC, MSFC, ESA and JAXA

2014-15 NEEMO

Mars analog demonstration with simulated time delay



2015 ISS On-Board

The first evaluation of assisted planning & re-planning system on Station

2003 Mars Exploration Rovers

Constraint Editor for Mission Planning and Long-Term Planning

2012 Mars Science Lab

Virtual collaborative activity planning & scheduling by science teams

LADEE 2012

Assisted re-planning

Playbook (2015)

TA 4.4.6, 4.5.2

Autonomous crew scheduling

- ISS astronauts can self-schedule mission activities independent of ground control
- Intelligent support system for planning to avoid and de-conflict plan violations and allow for rapid re-planning
- Technology demo on the International Space Station using tablet computers

Future human exploration missions

- Deep space missions (Mars, etc) will require crew to be more autonomous of mission control
- Activity scheduling is critical for mission execution and operations, but is tedious and complex
- Tools that support crew self-scheduling are essential for mission success

Ames Autonomy for Robotics

2002 Single Cycle Instrument Placement

Approach and place an instrument in one command cycle. Method has since been used on Mars with MER.

2007 Robotic Site Survey

Systematic autonomous survey with rovers. Field testing at Haughton Crater.

2014 Planetary Lake Lander

Adaptive science for dynamic phenomena in deep-space missions. Field testing in Chile.

2015 Astrobee Free-Flyer

Autonomous nav, docking and recharge, and mobile sensor IVA work on the ISS.

2005 Autonomous Visual Inspection

Robotic “walk around” inspection for future lunar sortie operations. Universal Executive and PLEXIL.

2010 ATHLETE Footfall Planner

Safe, energy-efficient walking with the ATHLETE robot on rough terrain.

2014 Advanced Navigation

Autonomous map and feature-based localization for future planetary rover missions.

2015 Self Driving Car

Adapt space robotics technlology to “fleet management” use.

Single Cycle Instrument Placement

TA 4.5.2, 4.5.7, 4.5.8

Overview

- Remote designation of targets for contact instrument measurement
- Autonomous navigation, arm deployment, and data collection
- Increased productivity, lower workload for ground operators

On-board Autonomy

- Robust, precision visual feature detection and tracking
- Autonomous vision-based navigation for terminal guidance
- Autonomous safe trajectory planning for robotic arm and contact instrument placement

Advanced Navigation (2014-)

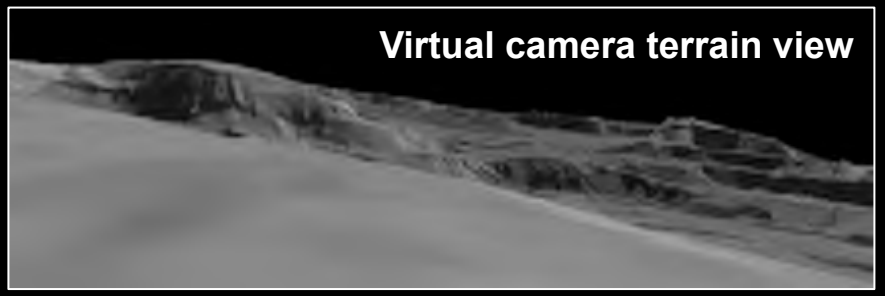
TA 4.2.6, 4.5.6, 4.5.7, 4.7.3

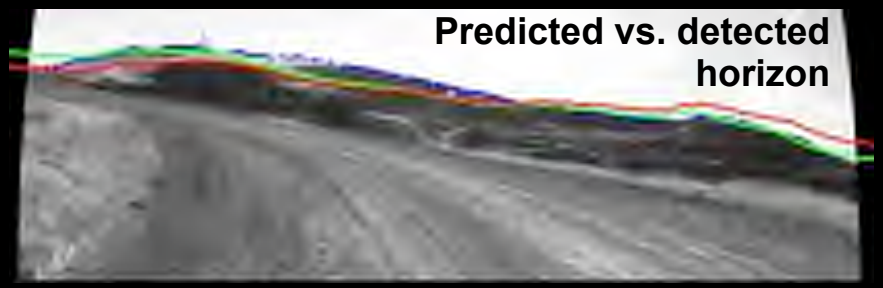
Overview

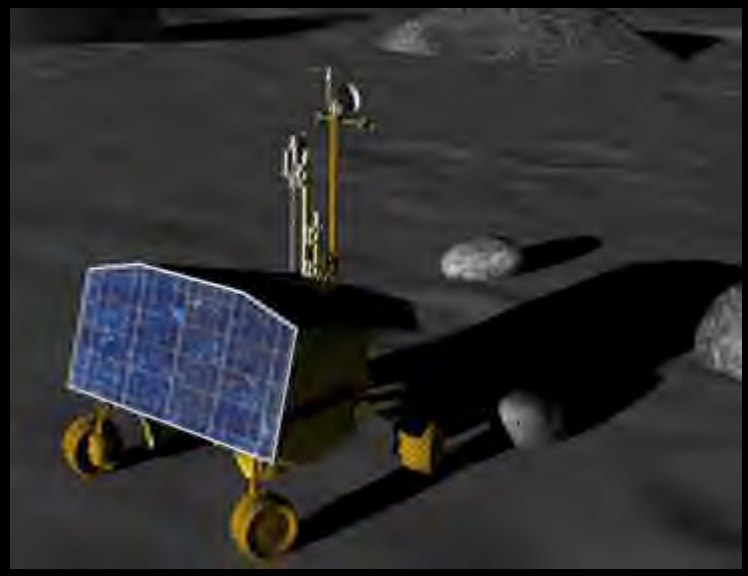
- Enabling technology for increased planetary rover autonomy
- Real-time surface positioning ("GPS without satellites") via on-board processing
- Infusion to Mars Science Lab (Curiosity) and Resource Prospector missions

Approach

- Stereo vision + 3D terrain model derived from from orbital imagery
- Determine position by comparing the horizon / terrain to 3D terrain model







NASA-Nissan Partnership (2015-)

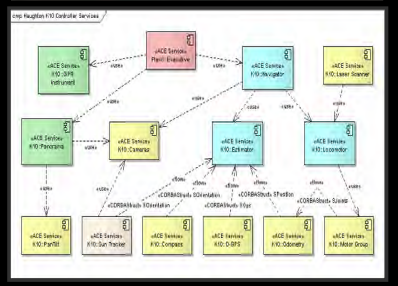
TA 4.4.8, 4.5.4, 4.5.5, 4.6.4

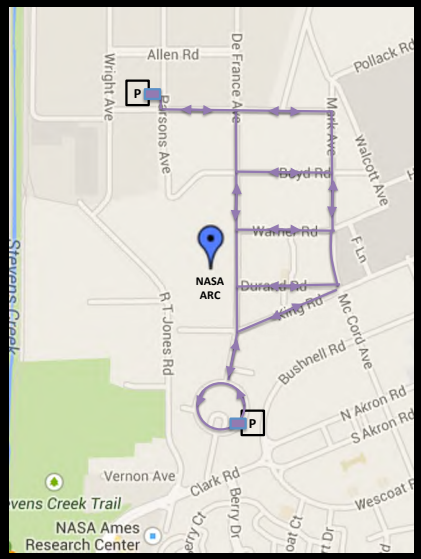
R&D agreement (5 year term)

- Autonomous vehicle systems
- Human-machine interface
- Network-enabled applications
- Software V & V
- Vehicle testing at NASA Ames

Current activities

- Adapt NASA telerobotic technology originally developed for planetary exploration
- Conduct joint development, testing, and assessment at Ames (urban scenario with dynamic hazards)
- Jan 2016 demo for Nissan CEO : Fleet management of multiple autonomous vehicles





Astrobee Space Robot (2015-)

TA 4.4.3, 4.4.8, 4.5.1, 4.5.7, 4.7.4

Overview

- Free flying robot for inside the ISS
- Astrobee will be used by flight controllers for mobile IVA sensing
- Astrobee will be used as a robotic testbed (like SPHERES)

Safe autonomous operations

- Task execution / notification
- Perching & station keeping
- Docking & resupply

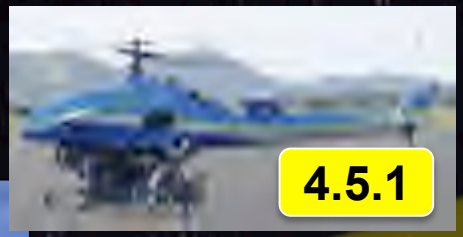
Concept of operations

- Mission control uploads plans to robot for autonomous execution
- Astrobee has on-board fault recovery (stop, terminate, return)
- Mission control can remotely intervene if needed

Ames Autonomy for Aeronautics

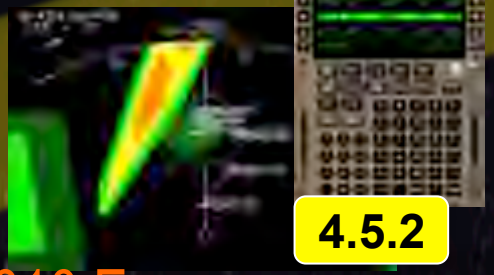
2004 Autonomous Rotorcraft

Automated reasoning in the context of autonomous rotorcraft operations.



2006-10 Intelligent Flight Control

Improved stability/control, adapts to uncertainties, reduced costs for FCS development



2010 Emergency Landing Planner

Decision support to the pilot of a damaged commercial transport aircraft

2012 Function Allocation

Automated ground-based separation assurance across increasing levels of autonomy

2011 Real-Time Prognostics

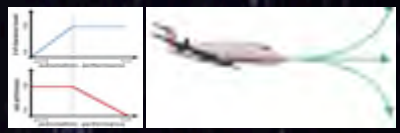
Predict remaining useful battery life

2015 sUAS Autonomy

Fully Autonomous urban deployment of sUAS—Vehicle Technologies and Airspace Management

2013 Prediction Uncertainty

Operators compensating for imperfect autonomy



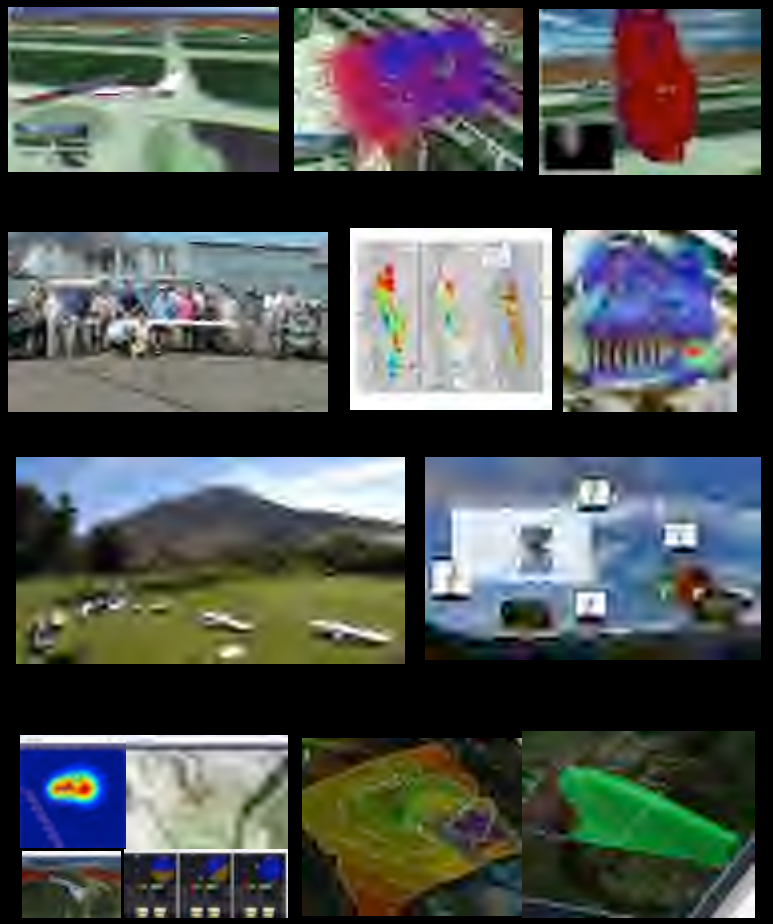
Payload Directed Flight

Overview

- The Payload Directed Flight project investigated autonomy and advanced GN&C allowing vehicles to operate relative to complex, large-scale, dynamic, and dangerous phenomena by "closing the loop" around payload sensors.
- Trajectory planning and optimization, trajectory-based control, real-time large-scale probabilistic estimation.

Applications and Flight Testing

- Autonomous Wildfire Identification and Tracking
- Autonomous Subsurface Earthquake Mapping Project in Surprise Valley, CA
- Distributed Collaborative UAS Swarm for Volcanic Plume Sensing in Turrialba, Costa Rica



Small UAS Autonomy (2015-)

TA 4.5.2, 4.5.7, 4.7.5, 15.6.1

The UTM architecture addresses mission planning and execution strategies for Small UAS (sUAS) operations to encompass:

>> Non-autonomous sUAS operations – for spontaneous launching of one or more sUAS by operator(s) to address an urgent need (e.g., for law enforcement and first responder scenarios)

>> Autonomous sUAS operations – for deliberate planned autonomous sUAS flights (e.g., search & rescue, cargo delivery, surveillance).

Research Focus:

1. Beyond visual line-of-sight
2. Reservation of airspace volume
3. Urban environments, higher density
   - >> Wind Accommodation
   - >> Sense and Avoid
   - >> On-board Autonomy

Function Allocation (2012)

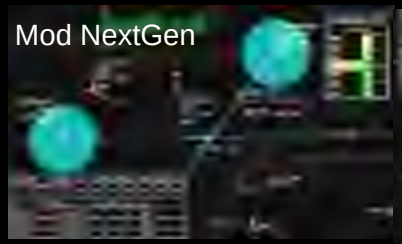
TA 15.5.1

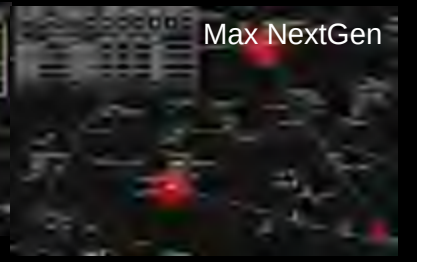
Overview

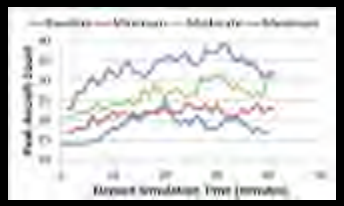
- Systematic investigation of automation and autonomy for air traffic control to increase capacity and efficiency
- Evaluation at different potential future stages of NextGen

Key Results

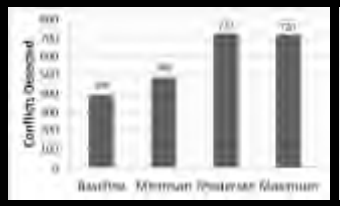
- The “Maximum NextGen” condition, in which controllers team up with autonomous separation assurance functions outperformed all others by far
- Increased decision support automation without paradigm shift caused additional complexities



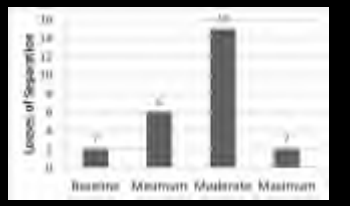




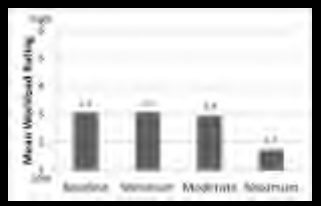
a/c count



detected conflicts

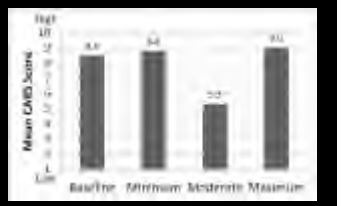


separation violations



workload

situation awareness



acceptability

Autonomy @Ames Summary

Heritage:

- Ames has a 25+ years heritage of conducting autonomy R&D and deploying autonomy in support of NASA's aeronautics and space missions

Currently:

- Ames has a robust and engaged autonomy activity:
  - Workforce: Over 300 staff members
  - Partnerships: Over 50 active partnerships with industry, academia, and government
  - Work: Applying autonomy to support NASA's aeronautics and human and robotic space missions, and actively engaged with industry partners in exploring additional application domains

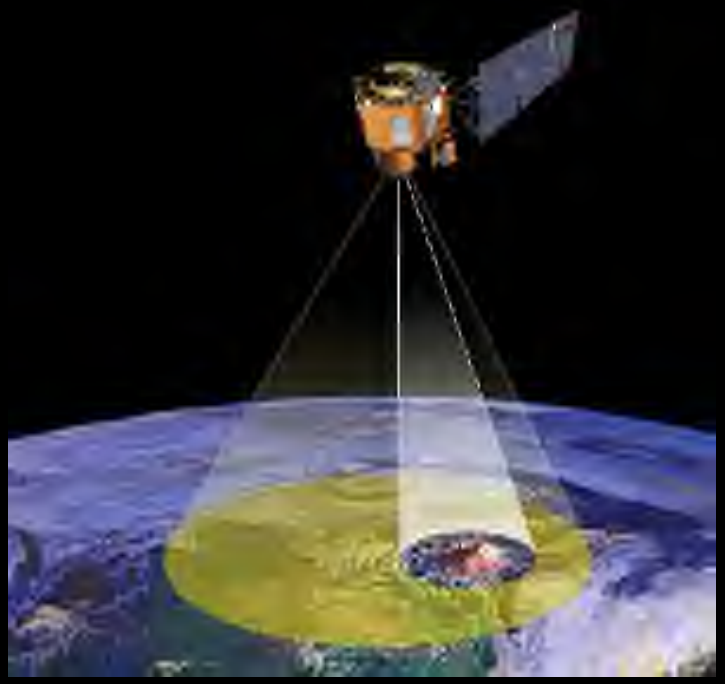
Future Commitment:

- Autonomy is one of Ames' 8 core competencies and Ames intends to apply Center level priority to NASA's needs in this domain

BACKUP

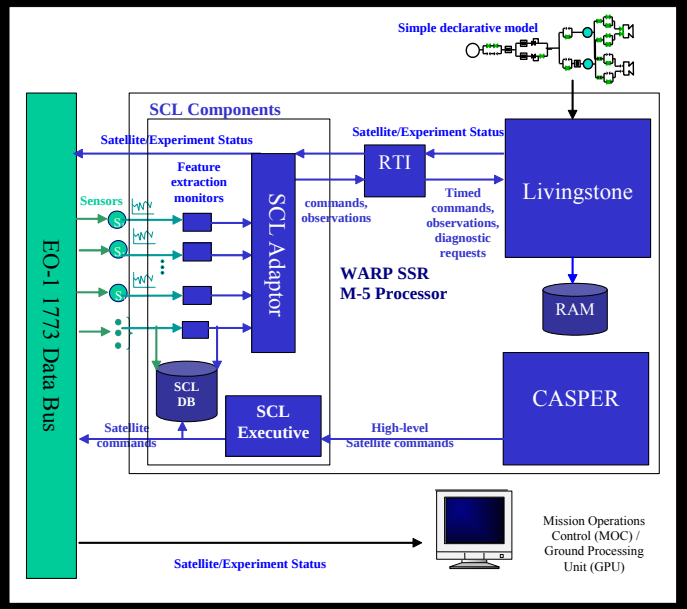
Fault Management on Earth Observing 1 (2003)

TA 4.5.1, 4.5.2,4.5.3



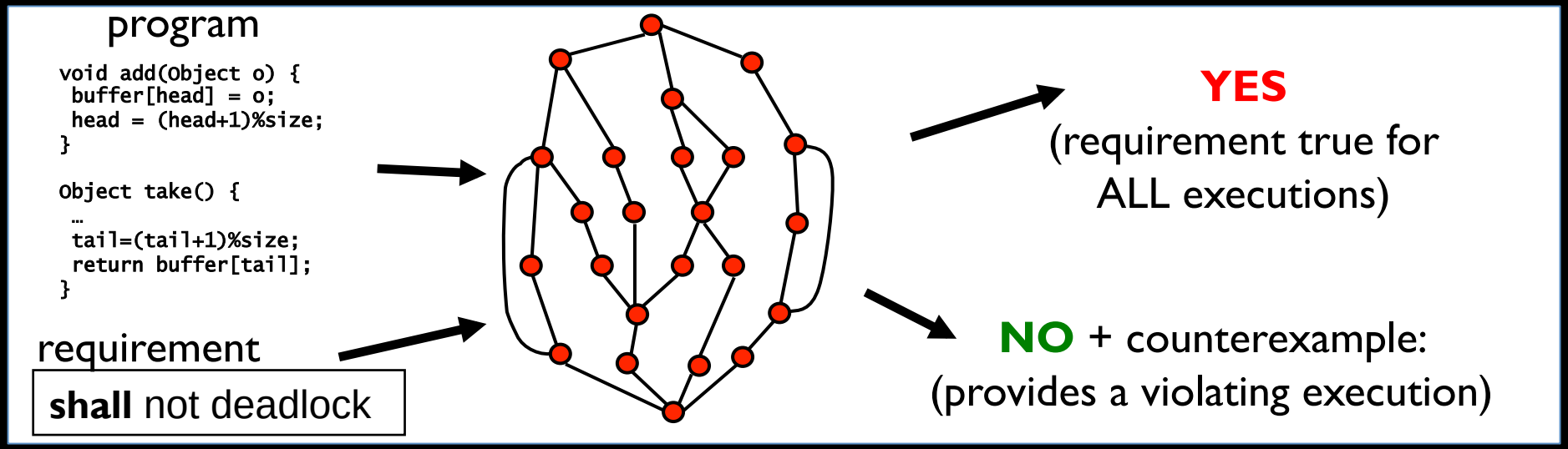
- During this demonstration, a model-based fault diagnostics component to the Autonomous Sciencecraft Experiment (ASE), led by Jet Propulsion Laboratory (JPL) and Interface and Control Systems (ICS), which flew on Earth Observing 1 satellite.

- EO-1 was the first flight deployment of this improved fault diagnosis technique.
- The diagnosis engine returned correct diagnosis in all on-board test scenarios.



Autonomy Software Verification (2000s)

TA 4.7.2, 4.7.5



PROBLEM: Testing may miss bugs that occur only under specific/rare circumstances.

ACHIEVEMENTS: The JavaPathfinder model checker automatically checks all possible executions of a program against its requirements, including concurrency. When a requirement does not hold, it provides a program trace that violates it.

IMPACT: JavaPathfinder is open source and has thousands of users worldwide. In autonomy, it was applied to the Remote Agent and K9 Rover Executive and found concurrency bugs in early design verification not found by testing. Recipient of *Outstanding Technology Development Award by Federal Laboratory Consortium Far West Region Awards, and most influential paper award in Software Engineering by the Automated Software Engineering conference.*

AUTONOMOUS MISSION OPERATIONS ON ISS (2014)
TA 4.5.1,4.5.2, 4.4.6

Demonstrate novel autonomous mission operations protocols and advanced technology onboard the International Space Station.

Astronauts autonomously managed multiple ISS systems over the course of several months of operations. Over the course of this experiment, astronauts performed over 90% of planned activities correctly without the aid of flight controllers on the ground, thereby demonstrating the capability to operate independently on future Exploration missions.

"It was great, thank you! Overall, the software was really good, better than I expected…we played with it once it was onboard and was really impressed with the capability, really amazing program."

ISS Crew debrief (Increment 40)

*"**"Situational Awareness was great BECAUSE of the AMO Software. I loved the AMO Software."***

ISS Crew debrief (Increment 41-42)

Planetary Lake Lander (2011-2014)

TA 4.1.4, 4.1.6, 4.3.6, 4.5.2, 4.5.8

Overview

- Analog for future probes to the methane seas of Titan (Titan Mare Explorer mission)
- Autonomously learns about dynamic environment
- On-board focusing of limited resources to improve science

Adaptive science

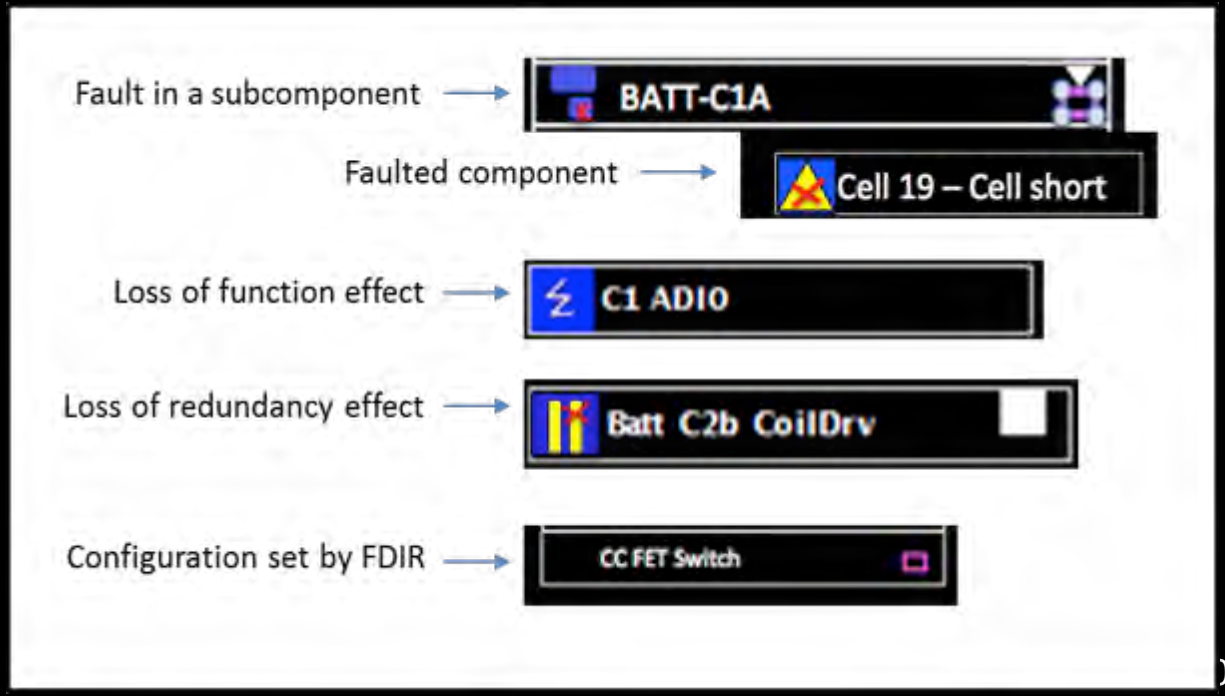
- Adaptive sampling (water column profiling)
- Dynamic event monitoring (storm detection / measurement)
- Adaptive shore approach
- Adaptive telemetry uplink (dynamic data triage)

ACAWS for EFT-1 (2014)

TA 4.5.1

Demonstrate novel Advanced Caution and Warning (ACAWS) technology during Exploration Flight Test 1 (EFT-1).

ACAWS monitored EFT-1 telemetry data to detect and isolate faults, and automatically determine loss of capability. ACAWS was designed using NASA developed and COTS software tools. ACAWS used novel system engineering processes to rapidly develop fault models. The ACAWS system was favorably evaluated by JSC flight controllers. ACAWS algorithms are now being migrated onboard for potential future use in Exploration spacecraft.

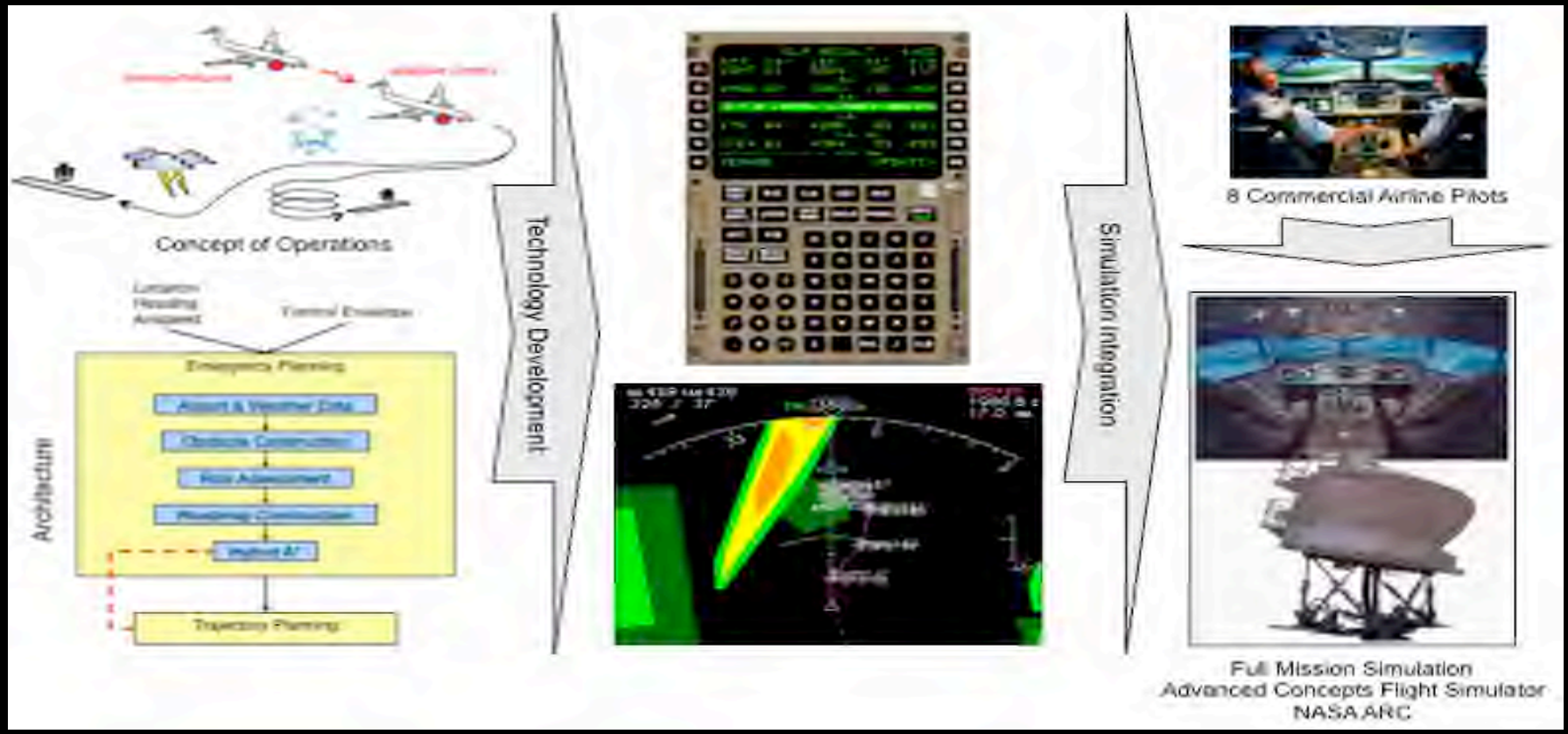


Emergency Landing Planner

Task: Provide decision support to the pilot of a damaged commercial transport aircraft, or decision support for air traffic controllers for medical emergencies.

Challenges: 100s of airports/runways, Dynamics, Path quality, 'Soft' obstacles

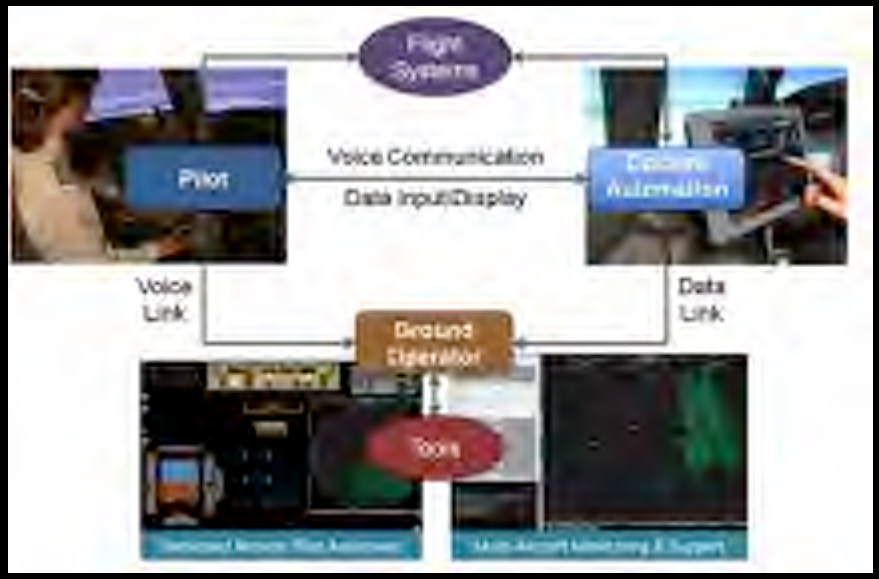
Impact: Evaluated in different weather and damage conditions. Pilot feedback overwhelmingly positive.



Improved Crew Operations

Increasingly Autonomous Systems

- Automated Procedures and Checklist Interactions
- Aircraft Monitoring & Assessment
- Predictive a/c state and clearance compliance monitoring
- Detecting, diagnosing and responding to non-normal conditions
- Autonomous Flight Planning



Human/Autonomy Teaming (HAT)

- Function Allocation (FA) and Crew Resource Management
  - Adjustable, adaptive, and/or mixed initiative autonomy
- Collaboration tablet (shared documents, text & video chat, voice interface)
- Human-Machine Interfaces (HMI)
  - Transparent and collaborative autonomy; Multi-modal interaction
- Futuristic Flight Deck and/or Ground Station Technologies
  - Flight, Automation, and Information Management (FAIM) system
  - Simplified Autoflight Testbed (SAT)

V&V of Uncertainty

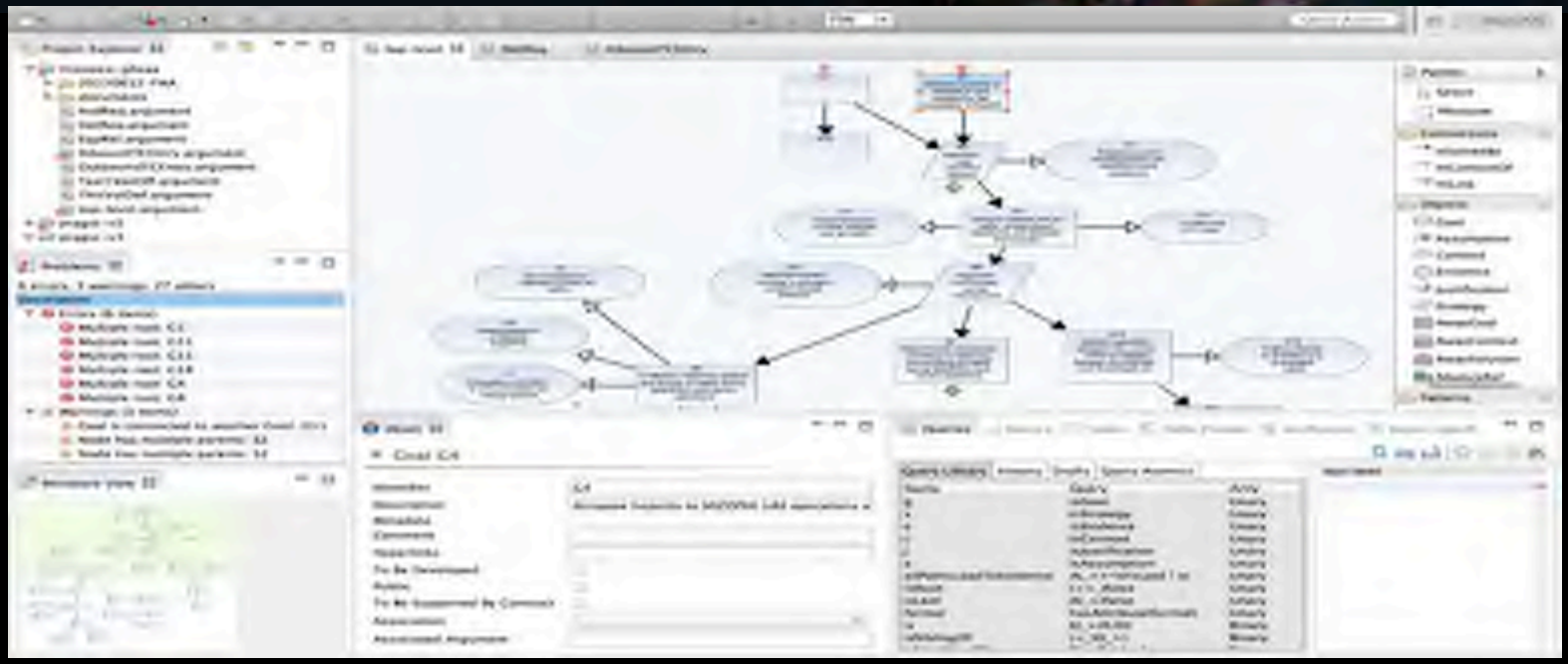
ACAS X:
the next generation onboard collision avoidance system, to replace TCAS

PROBLEM: Software for autonomy is designed to deal with uncertainty and is hard to verify. For example, ACAS X is based on models that capture pilot or intruder behavior and state estimation probabilistically.

ACHIEVEMENTS: 1) VeriCA – tool for design and verification of probabilistic systems. 2) RLES – tool for automatic generation of high probability aircraft scenarios that trigger undesirable behavior in ACAS X.

IMPACT: Both tools applied to ACAS X, and transferred to the FAA. VeriCA identified a design problem of an early ACAS X prototype. RLES is used by ACAS X team to generate scenarios leading to Near Mid Air Collision. *NASA Honor and conference best paper awards.*

Safety Cases for Autonomy



PROBLEM: FAA's safety case requirement for 'non-standard' UAS operations presents very high bar for entry to the NAS.

ACHIEVEMENTS: AdvoCATE tool facilitates development of safety cases through semi-automated generation, reducing barrier to autonomous missions and supporting eventual certification.

IMPACT: Ames used AdvoCATE to create the first operational safety case accepted by the FAA for a Ground-based Sense and Avoid (GBSAA) mission. This was also the first safety case for civilian UAS in the NAS. *NASA Honor and conference best paper awards.*